COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE 122 (2015) 491–502

journal homepage: www.intl.elsevierhealth.com/journals/cmpb

Parameter-dependent behavior of articular cartilage: 3D mechano-electrochemical computational model

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ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form
2 September 2015
Accepted 23 September 2015

Keywords:
Parametric analysis
Articular cartilage
Mechano-electrochemical model
Cartilage Young's modulus
Ion diffusivity
Ion activity coefficient

ABSTRACT

Background and objective: Changes in mechano-electrochemical properties of articular cartilage play an essential role in the majority of cartilage diseases. Despite of this importance, the specific effect of each parameter into tissue behavior remains still obscure. Parametric computational modeling of cartilage can provide some insights into this matter, specifically the study of mechano-electrochemical properties variation and their correlation with tissue swelling, water and ion fluxes. Thus, the aim of this study is to evaluate the influence of the main mechanical and electrochemical parameters on the determination of articular cartilage behavior by a parametric analysis through a 3D finite element model.

Methods: For this purpose, a previous 3D mechano-electrochemical model, developed by the same authors, of articular cartilage behavior has been used. Young's modulus, Poisson coefficient, ion diffusivities and ion activity coefficients variations have been analyzed and quantified through monitoring tissue simulated response.

Results: Simulation results show how Young's modulus and Poisson coefficient control tissue behavior rather than electrochemical properties. Meanwhile, ion diffusivity and ion activity coefficients appear to be vital in controlling velocity of incoming and outgoing fluxes.

Conclusions: This parametric study establishes a basic guide when defining the main properties that are essential to be included into computational modeling of articular cartilage providing a helpful tool in tissue simulations.

1. Introduction

Articular cartilage plays a vital role in the function of diarthrodial joints [1]. The initial event that triggers pathological process of cartilage degeneration is still unknown [2]. Hence, to investigate the initiation of cartilage diseases, most important parameters that control its behavior should be determined. So far, the common method to accomplish that, are specific experimental assays [3–5]. However, these techniques

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http://dx.doi.org/10.1016/j.cmpb.2015.09.018
0169-2607/

require high costs and elevate time consuming. Besides, experimental approaches limit the study of parameters in an individual manner. To solve these problems, in the last decade, it has emerged the use of computational models to simulate cartilage behavior [6,7] as well as materials mimicking cartilage [8,9]. Therein, the finite element method is the most used [10,11]. In the literature many material models for articular cartilage can be found. These models range from relatively simple, including the biphasic nature of the tissue [12,13], to models that include descriptions of all major individual components of the cartilage [14–18]. However, the main parameters to consider in these simulations remain still obscure since the requirements of a material model are highly dependent on the particular question under research. In general, the more features of the composition and structure of articular cartilage are included, the larger the number of material parameters that must be determined, and the more computationally expensive the model becomes. Hence, we should always try to use the simplest model with the lowest number of tissue properties to obtain the required data but without compromising the predictive capacity of the computational model.

The present parametric study faces important questions like: (i) is the weakening of collagen matrix enough for tissue to swell or it is required to consider the proteoglycans content decrement? (ii) is Poisson coefficient an essential parameter in articular cartilage modeling? (iii) which phenomena, mechanical, chemical or electrical do manage tissue behavior? (iv) are they combined to control tissue behavior or one of them is more relevant?

To solve these questions a previous developed three-dimensional mechano-electrochemical model [16,17] has been used to analyze and quantify the influence of each parameter variation into cartilage behavior. Specifically, Young's modulus (E), Poisson coefficient (ν), cation and anion diffusivities (D^+ and D^-, respectively), cation and anion activity coefficient (γ^+ and γ^-, respectively) changes have been addressed. To our knowledge, this is the first parametric study that determines the influence of these properties in an isolate manner in cartilage behavior, resulting in a basic guide to select the main parameters required for articular cartilage simulation. Note that the model includes essential biological phenomena, previously described in literature, that affect cartilage behavior (diffusive-convective events and mechano-electrochemical effects) [14,19,20]. However, it excludes those that experimentally show less influence as the viscosity of the solid matrix. Often, material models of articular cartilage exclude this effect since in short-term type of simulation the viscosity does not play a great role and articular cartilage appears as an elastic solid with lower compressibility [21,22]. Results show that (i) only collagen degradation is required to promote tissue swelling; (ii) minimal variation in ν generates significant differences in tissue swelling and water and anion fluxes; (iii) variation in D^+ and D^- seems to have less influence in capturing cartilage behavior than the mechanical parameters, however, they control the velocity of ion fluxes and finally, (iv) similar to D^+ and D^-, γ^+ and γ^- show lower influence into tissue deformation (one order or magnitude less) than the studied mechanical properties.

The presented parametric study is a helpful tool to decipher the effects on cartilage simulated behavior when varying Young's modulus, Poisson coefficient, and ion activity and diffusivity coefficients. Besides, the inclusion of repulsion phenomenon due to negative fixed charges attached to proteoglycans and the 3D nature of the model, present this algorithm as a new and easy method for the analysis and selection of the main parameters to include in cartilage computational models.

2. Material and methods

Based on our previous work [16] four phases are considered: negatively charged porous-elastic solid (s), fluid (f), cations (+) and anions (−). These phases dynamically interact with each other triggering essential mechano-electrochemical phenomena for cartilage maintenance (for more details see [16–18]).

2.1. Mechano-electrochemical model

2.1.1. Governing equations

The governing equations of the model are based in the momentum and mass balance for the whole mixture and the charge balance for each ion. The relation between the four basic unknowns ($\mathbf{u}^s$ the displacement of the solid matrix, ε^w the chemical potential of water, ε^+ and ε^- the electrochemical potentials for cations and anions, respectively) are summarized below:

Momentum balance equation for the whole mixture

$$\nabla \cdot \underbrace{\boldsymbol{\sigma}}_{\boldsymbol{\sigma}^f+\boldsymbol{\sigma}^c+\boldsymbol{\sigma}^s} = 0. \tag{1}$$

Mass balance equation for the whole mixture

$$\nabla \cdot \mathbf{v}^s + \nabla \cdot \mathbf{J}^w = 0. \tag{2}$$

Charge balance equation for each studied ion

$$\frac{\partial(\Phi^w c^+)}{\partial t} + \nabla \cdot \underbrace{\mathbf{J}^+}_{\text{diffusion}} + \nabla \cdot \underbrace{(\Phi^w c^+ \mathbf{v}^s)}_{\text{convection}} = 0, \tag{3}$$

$$\frac{\partial(\Phi^w c^-)}{\partial t} + \nabla \cdot \underbrace{\mathbf{J}^-}_{\text{diffusion}} + \nabla \cdot \underbrace{(\Phi^w c^- \mathbf{v}^s)}_{\text{convection}} = 0. \tag{4}$$

In these equations, $\boldsymbol{\sigma}$ corresponds to the stress tensor related to the total mixture while and $\boldsymbol{\sigma}^f$, $\boldsymbol{\sigma}^c$ and $\boldsymbol{\sigma}^s$ are the stress tensors of the fluid, chemical and solid phases respectively. $\mathbf{v}^s = \partial \mathbf{u}^s / \partial t$ refers to the velocity of the solid matrix. Note that in Eq. (1), body and inertial forces are neglected. Moreover, small strain formulation is adopted. Besides, c^+ and c^- are cation and anion concentrations respectively. Finally, Φ^w corresponds to the porosity of the tissue [18]. Regarding the different fluxes, the water flux, $\mathbf{J}^w$, cation flux, $\mathbf{J}^+$, and anion flux, $\mathbf{J}^-$, can be written as a combination of the electrochemical potentials,

$$\mathbf{J}^w = -\frac{RT\Phi^w}{\alpha}\left(\nabla\varepsilon^w + \frac{c^+}{\varepsilon^+}\nabla\varepsilon^+ + \frac{c^-}{\varepsilon^-}\nabla\varepsilon^-\right), \tag{5}$$